PRESENT-DAY MARS' WATER CYCLE : NEW VIEWS AND BLIND PERSPECTIVES...

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Introduction

Addressing recent cimate changes on Mars necessarily requires a succesful representation of present-day Mars water cycle. Decades of observations and modeling efforts have been conducted that now allow to elaborate a new, yet incomplete, picture, of the seasonal activity of water on Mars. Here I explore the various observational and theoretical studies that have been conducted to date, and attempt to present a concise explanation of the major physical mechanisms that command the seasonal and geographical variability of present-day Mars water cycle, as inferred from the combined analysis of measurements and climate model simulations. Remaining issues and enigmae are presented as well. *Note: Most of the material presented here is extracted from Mars' water cycle by Montmessin et al. (2012) in the Mars atmosphere and climate Book (ed. R.M. Haberle et al.)*

Observations

The first systematic mapping of water vapor with complete spatial and seasonal coverage was obtained by the Martian Atmospheric Water Detector (MAWD) on-board the *Viking 1* and *2 Orbiters* using the 1.38 µm absorption band of water vapor. The MAWD observations (Figure 1) covered more than one Martian year from June 1976 through April 1979 [1]. For a long time these data formed the classical framework constraining Martian water cycle models.

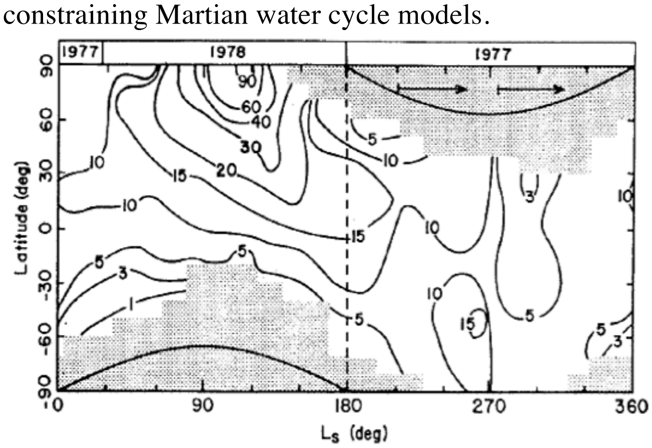

Figure 1: The first annual monitoring of water vapor provided by the Viking/MAWD instrument [1].

An impressive dataset for water vapor has now been assembled from the observations made by the various orbital platforms that have monitored water in basically all its phases (we will however restrict the following discussion to water vapor that benefits from the densest observational dataset to date). The combination of these recent observations now allows a good overall characterization of the distribution of water vapor as a function of season and location as shown in Figure 2. The current climate has a global annually-averaged column abundance of about 10 pr-μm, with higher abundance at high latitudes in the hemisphere where it is spring or summer. The northern hemisphere summer high-latitude maximum reaches a peak column abundance of roughly 50 pr-μm while the corresponding southern hemisphere summer maximum is weaker and more variable from one Martian year to the next, usually reaching about 25 pr-μm.

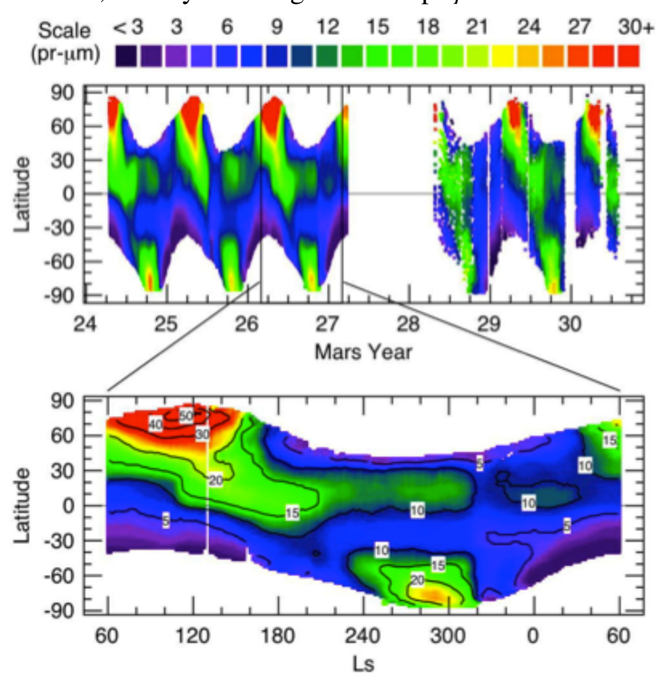

Figure 2: Multi-annual tracking of water vapor as compiled by M.D. Smith from MGS/TES and MRO/CRISM data.

Although there is evidence of interannual variation in water vapor abundance, the global seasonal trend follows the same general pattern from year to year (Figure 2). The highest water vapor column abundance occurs poleward of 70° N latitude during early summer (Ls = 110°–120°) after sublimation of north polar cap (NPC). At this time, water vapor abundance decreases monotonically from north to south with an abundance of roughly 50 pr-μm near the pole, 20 pr-μm at 15° N latitude, and less than 5 pr-μm in the southern hemisphere. After Ls = 130°, water vapor abundance rapidly decreases in the northern polar region falling below 10 pr-μm by Ls = 170°. This decrease in the north is partially balanced by a corresponding increase in water vapor that moves to the south as the season progresses. At 45° N latitude, water vapor reaches a maximum abundance at Ls = 135°, while at 30° N latitude maximum water vapor is attained at Ls = 150°. By Ls = 170° a well-developed maximum in water vapor develops between the equator and 30° N latitude, which persists throughout northern hemisphere fall and winter until Ls = 40° in the following year when water vapor begins to rapidly increase again throughout the northern hemisphere.

In the southern hemisphere there is a gradual rise in water vapor abundance throughout the southern spring (Ls = 180°–270°) as water vapor is transported southward from the northern hemisphere summertime maximum. In late southern spring (Ls = 220°) water vapor increases at high southern latitudes with the sublimation of the southern seasonal polar cap. Maximum southern hemisphere water vapor occurs around Ls = 290°. The peak abundance of water vapor at the southern hemisphere summer maximum is somewhat variable, but is generally about one-half that of the maximum value during northern hemisphere summer.

After Ls = 300° water vapor abundance near the south pole decreases, and after Ls = 330° the decrease in water vapor becomes planet-wide. The period between Ls = 330° and 40° is the driest time of the year overall with 5 pr-μm or less water vapor column abundance over most of the planet. Water vapor abundance begins to increase significantly once again in the northern hemisphere after Ls = 40°, steadily climbing to its peak value once again at Ls = 120°, while the abundance of water vapor in the southern hemisphere remains mostly unchanged at a very low level until southern spring.

First Theoretical studies

The use of modeling tools is a long-standing activity in the study of Mars' water cycle. Models provide a theoretical framework in which physical processes can be isolated and further quantified. The theoretical study of the Mars water cycle was largely inspired by the desire to analyze and understand the MAWD observations of water vapor.

As indicated by [2]; three major questions arose from the MAWD observations: (1) What is the cause of the observed north to south asymmetry in water vapor abundances?, (2) Does the annual behavior of water correspond to a state of equilibrium, repeating itself year after year?, and (3) What controls the changes of the bulk abundance of water in the atmosphere? Nearly two decades after Viking, various orbiting experiments have shown that the behavior of water basically reproduces the same seasonal trends year after year and is therefore evolving in a stable manner (see Figure 2).

[3] was the first to investigate the latitudinal and seasonal variability of water vapor observed by MAWD, hypothesizing that exchanges of water were uniquely driven by deposition and sublimation of ice at and from the surface. The model of [3] used an add-hoc representation of transport where tracer advection was modeled by horizontal diffusion with a prescribed timescale. The modeling work of Davies captured two of the most salient features of the present-day water cycle: (i) the water cycle is essentially controlled by the seasonal variation of temperature in the polar regions, and (ii) the water cycle is in equilibrium with the present-day orbital configuration of Mars, the latter controlling insolation distribution between the polar and the equatorial regions.

WORK	MODEL TYPE	MAIN CONCLUSIONS
Davies, Icarus, 1981	• Altitude independent (full column) • Prescribed horizontal mixing = meridional advection • Column saturation limit: excess of water is precipitated at the ground	**1.Viking observations can be reproduced;** 2.North-to-south asymmetry can be simulated with a seasonal dichotomy of mixing (north vs. south).
Jakosky, Icarus, $1983_{a,b}$	Same 1D-basis as Davies (1981) + Regolith adsorption/desorption included + More consistent horizontal mixing representation	Discounts Davies's conclusions: **1.Circulation is not the sole driver** **2.Regolith accounts for 40% of seasonal variations.** 3.Cycle is equilibrated minus a small loss at the south pole
James, Icarus, 1985	Same 1D-basis as Davies (1981) + CO_2 sublimation flux included as an additional advection term	**North-to-south asymmetry is caused by the asymmetric CO_2 cycle.**

Table 1: A compilation of major 1D theoretical works performed in the 80's by various authors. The Table gives a brief summary of model hypothesis and of the major conclusions reached by the studies.

The first comprehensive assessment of the water cycle performed by [4]-[5] followed a similar approach but with the inclusion of a "wettable" regolith in addition to atmospheric transport and surface-atmosphere exchanges. [4]-[5] acknowledged the central role played by the perennial polar caps in the entire cycle process and also concluded that a near-surface reservoir was necessary for successfully reproducing the seasonality of water vapor, estimating it to account for 10 to 40% of the atmospheric water variability. A compilation of all 1D studies performed until 1990 is given in Table 1 with major conclusions highlighted.

The first study including a non-parametric representation of atmospheric water transport was published by [6], who used a two-dimensional axi-symmetric circulation model to analyze the transport mechanism controlling water extraction from its northern pole source region in spring and summer. The conclusion of these authors emphasized two aspects of this critical stage of the water cycle. First, a sea-breeze circulation at the edge of the north residual cap was identified as the sole dynamical mechanism capable of carrying water equatorward. Second, the sea-breeze mechanism was predicted to be too weak in intensity to reproduce the observed summer moistening of the nonpolar region. Something was lacking in the model that Haberle and Jakosky (1992), confirming earlier statements by Jakosky (1983a, b), attributed to the seasonal "breathing" of the mid-latitude regolith through adsorption and desorption of water.

The advent of General Circulation Models (GCM)

It is now known that all the studies performed to that date were missing a fundamental aspect of the Mars water cycle. The advent of three-dimensional GCMs, with a self-consistent determination of the wind and temperature fields was the key to a physically valid reproduction of the water vapor seasonal behavior [7, 2, 8]. With these models, the need to include a regolith as a seasonal water reservoir has become less obvious. [7] claimed that the regolith has a large role as an exchangeable seasonal reservoir, but their conclusion was contaminated by an error in their model. The overstated importance of the regolith was likely the result of simpler models attempting to compensate for an inadequate transport description. Mars circulation is three-dimensional in essence, and the existence of residual components in the circulation, *i.e.* travelling and stationary atmospheric waves, accounts for a significant fraction of horizontal transport that parametric or zonally symmetric circulation models have difficulty representing. Additionally, the use of GCMs has allowed an evaluation of the role of clouds in the seasonal fate of water.

The current picture of Mars' water cycle

Closure of the water cycle on an annual basis is driven the by rapid atmospheric transport processes and by the interactions between the surface and the atmosphere through seasonal ice sublimation and reformation. This implies that the present-day water cycle reflects equilibrium with the current climatic conditions, which favor the storage of water in the northern hemisphere.

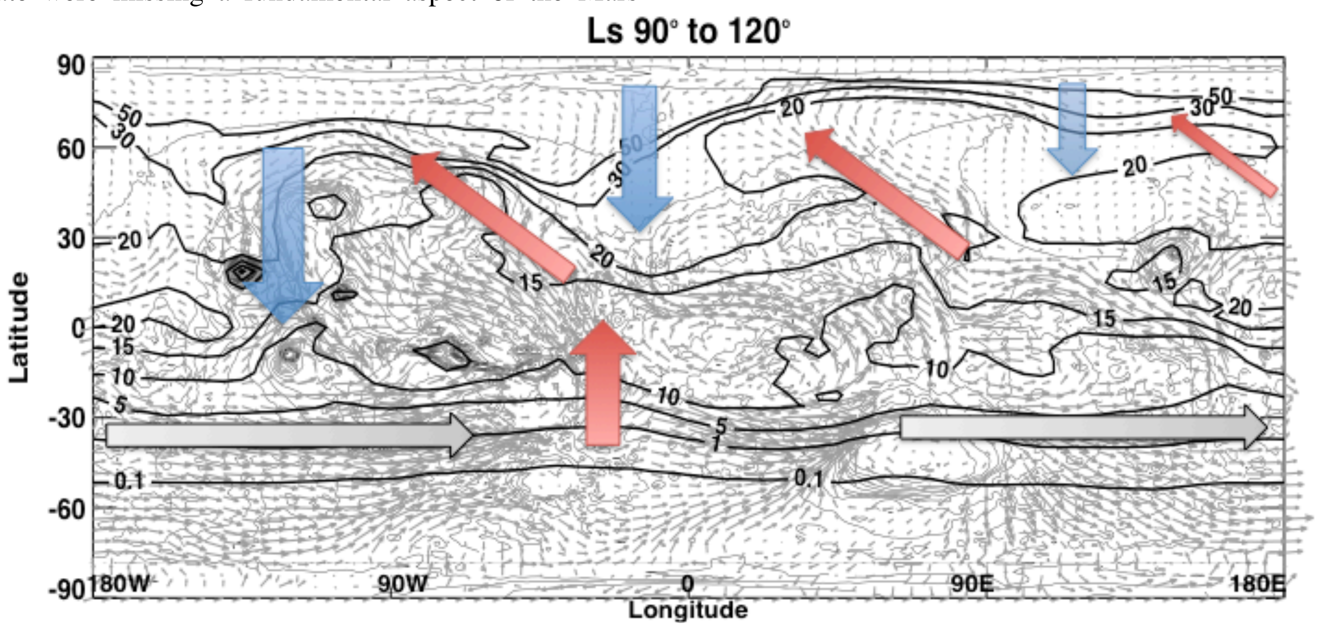

Figure 3: GCM results [8] showing maps of water vapor column-abundances (scaled to a reference pressure of 6.1 mbar, units in pr-μm) averaged over the northern and southern solstice seasons (upper and lower plots).

Horizontal wind is indicated by the grey arrows to detail the nature of the near-surface (z ~ 3 km) circulation during these periods. A stationary wave-3 pattern (-130°, -20° and 90° in east longitudes, highlighted by the blue and red arrows) dominates the northern summer.

The most important process in the Mars water cycle activity is the exchanges between the northern polar cap, by far the major exposed reservoir of water on the planet, and the atmosphere, which controls the spring/summer extraction and the winter/spring return of water to the poles. In this picture, the role of dynamic phenomena can be separated into two main components: the zonally symmetric Hadley circulation is the prime regulator of water exchanges between the two hemispheres, whereas the residual, non-zonal component of circulation (planetary waves) control the poleward and equatorward fluxes at mid and high latitudes of both hemispheres.

The conditions within which water is exported in the spring/summer from the edge of the north polar cap (NPC) to the lower latitudes are now identified. [9] specifically investigated the nature of summertime water transport from the north pole. By comparing various transport formulations (diffusion approach, 2-D zonally symmetric and full 3-D GCM), [9] was able to establish the three-dimensional nature of the summertime water advection from high to mid northern latitudes. The surface thermal inertia on Mars exhibits a distinct wave-3 zonal structure in the 45° to 70° N latitude range that imposes significant surface temperature contrast with longitude. Together with the wave-3 structure of topography associated with Arcadia, Acidalia and Utopia Planitiae, surface properties force the development of a zonally asymmetric summertime circulation in that latitudinal band. These same regions are known to enhance transient eddy activity in winter, being referred to as the "storm zones" of Mars [10]. Water vapor subliming off the NPC is therefore locked into a wave-3 configuration, confining equatorward transport of water within three longitudinal corridors located at 130° W, 20° W and 270° W (Figure 3).

A fundamental aspect of the Mars water cycle concerns its ability to compensate the summertime extraction of water from the poles by an equivalent return flow (minus the permanent loss on the residual CO_2 cap) during the rest of the year. Since the work of [7], the process by which this occurs is now better understood and has been studied in greater detail thanks to numerous observations

Seasonal CO_2 ice caps are places of highly unstable baroclinic disturbances, which participate in the maintenance and regulation of the winter/springtime poleward retreat of water. From the early phase of the retreat, near Ls = 320°, seasonal water ice frost is involved in a sublimation-recondensation mechanism, consisting of poleward redeposition of newly sublimed water. This mechanism operates until the final stages of the recession after Ls = 70°. The seasonal cap edge consequently sees a significant and steady increase of its water ice composition during the retreat phase, with an equivalent thickness of water ice growing from 20 μm during the early stage up to >200 μm before the final sublimation event. This is the essence of the mechanism proposed by [7], which appears to prevail in the seasonal recession of the southern hemisphere frost as well.

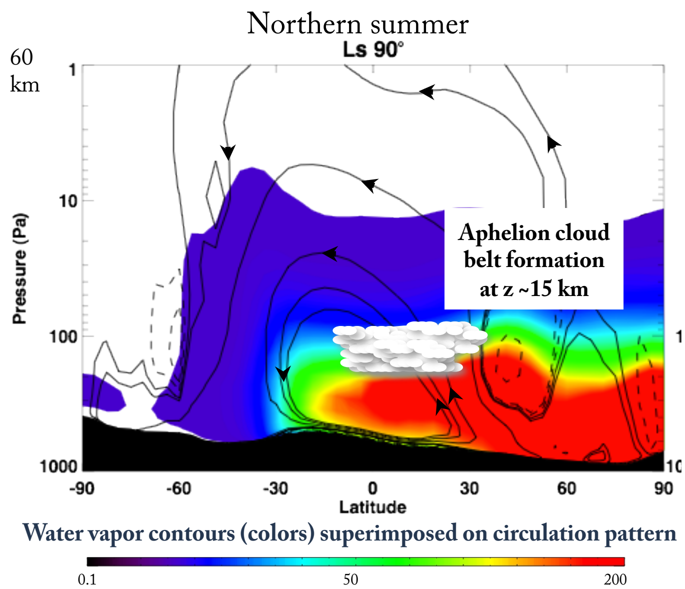

Figure 4: Latitude-altitude cross-sections of the time and zonally averaged component of Mars circulation @ northern summer solstice superimposed with shaded contours of water vapor mass mixing ratios. The so-called Clancy effect, as described by [11], is evident in this figure with clouds blowking southward transport of water in the tropics.

The role of clouds highlighted

Keyed to these exchanges, water ice clouds are the unique atmospheric conveyors of water in the regions and at the seasons where low temperatures impose very low water vapor abundance. This occurs in the northern spring and summer tropics when clouds are predicted to unlock a net transfer of 10^{12} kg water to the southern hemisphere through the upper branch of the solstitial

Hadley cell (so-called “Clancy” effect, see Figure 4). Similarly, clouds delay the winter/spring return of water to theregions since they can be advected by the equatorward motions of the travelling disturbances that develop at the edges of the polar vortices, ending up in a significant build-up (a factor of two) in the annually-averaged concentration of water in the tropics.

Remaining issues and paths for improvements

The fact that many water cycle models have been able to reproduce the salient features of the seasonal cycle of water vapor without the action of a regolith suggests minor to moderate influence of the seasonal storage and release of water in and from the subsurface. Regolith representation is hampered by the lack of knowledge of some major parameters, in particular the regolith adsorptive capacity whose spatial variability is hard to constrain without relevant *in situ* measurements. While the role of the regolith appears fundamental for the evolution of water on geologic timescales, its influence on the diurnal and seasonal fate of water remains to be quantified.

Climate modelers have undertaken important evolutions that go into the direction of improved water cycle mechanism representation. The community is now making the transition from “Do I have the correct climate model to study the water cycle?” to “Can I model the climate correctly without the water cycle?”. Obviously, such ambition comes along with increased complexity. Several areas require further sophistication of their theoretical foundations, such as the coupling of dust and water in the atmosphere and on the surface, which subsequently affect the radiative properties and hence the climate. However, the growing body of observational constraints is far from being exploited, and sufficient material is now at the disposal of the community to further the knowledge of the present-day Mars water cycle.

References

[1] Jakosky and Farmer, Icarus, 1982, [2] Richardson and Wilson, JGR, Planets, 2002, [3] Davies, Icarus, 1981, [4]-[5] Jakosky, Icarus, 1983a-b, [6] Haberle and Jakosky, JGR, (990, [7] Houben et al., JGR Planets, 1997, [8] Montmessin et al., JGR Planets, 2004, [9] Richardson, 1999, [10] Hollingsworth et al., Nature, 1996, [11] Clancy et al., Icarus, 1996.